NASA TECHNICAL NOTE

NASA TN D-2202

NASA TN D-2202

57635

PROPERTY OF

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES

by Thomas W. Orange

Lewis Research Center
Cleveland, Ohio

20011129 150

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1964

TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES

By Thomas W. Orange

Lewis Research Center
Cleveland, Ohio

Reproduced From Best Available Copy

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce, Washington, D.C. 20230 -- Price $0.75

TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES

by Thomas W. Orange

Lewis Research Center

SUMMARY

The cryoforming (cryogenic stretch forming) process appears to be a promising method for the fabrication of lightweight high-strength pressure vessels. The purpose of the present investigation was to determine the tensile characteristics of cryoformed AISI 301 stainless steel at temperatures from ambient to -423° F. Cylindrical pressure vessels that were fabricated by cryoforming were cut into coupons from which smooth and sharp-notch tensile specimens were made. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity. These specimens were tested at ambient temperature, -320° F, and -423° F. Results were compared with like properties for AISI 301 stainless steel cold-reduced 60 and 70 percent. [Cryogenic testing] 2

The ultimate and yield strengths of the cryoformed AISI 301 increased by about 50 percent as the test temperature was reduced from ambient to -423° F but were lower than those of the AISI 301 cold-reduced 60 and 70 percent. Weld efficiencies for the cryoformed material were above 93 percent for all cases, and weld strengths were higher than for roll-planished fusion welds in cold-rolled austenitic stainless steels. The cryoformed material was notch ductile at ambient temperature but became notch sensitive at cryogenic temperatures, whereas the cold-reduced material retained its notch toughness down to -320° F and diminished somewhat below this temperature. Evidence exists to suggest that the low-temperature notch toughness of austenitic stainless steels work-hardened at subzero temperatures can be improved by a change in the alloy content. A definite conclusion cannot be reached at present, but it appears that lowering the carbon, silicon, and manganese contents to very low levels might effect a significant improvement in notch strength with little loss of tensile strength.

INTRODUCTION

Space vehicles that use liquid oxygen and liquid hydrogen as propellants require materials that have high strength-to-weight ratios and adequate resistance to brittle fracture at extremely low temperatures. The 18-8 stainless steels when cold-reduced possess these qualities. This report presents the re-

sults of a program evaluating the strength and fracture toughness of AISI 301 stainless steel that received its cold-working by biaxial straining at -320° F instead of the normal room-temperature cold-rolling procedure.

AISI 301 stainless steel, when cold-reduced 60 to 70 percent, appears to be an attractive material but presents fabrication problems. Fusion- or spot-welding produces a local annealing effect in the work-hardened parent metal that may drastically weaken the joint; the compensatory reinforcement then incurs a weight penalty and may introduce discontinuity bending stresses.

The ideal solution would be to fusion-weld while the material is in the annealed condition then work-harden the entire structure including the weld area. Unfortunately, most space vehicle structures could not then be cold-rolled to finished shape, especially large propellant tanks.

One approach to this ideal is the cryoforming (cryogenic stretch forming) process described in reference 1, whereby a vessel is made by welding annealed sheet material into a "preform" vessel shape and then strengthened and sized by pressurizing beyond the elastic limit at -320° F. The mechanical deformation and the metallurgical transformation that occur produce high strength in both the parent metal and the weld, and thus the need for weld reinforcement is eliminated. Although originally developed for the production of solid-propellant rocket motor cases, this type of fabrication would be desirable for lightweight high-strength pressure vessels for use at cryogenic temperatures.

The cryoforming process depends on the ability of metastable austenitic stainless steels to gain strength by transformation from the austenitic to the martensitic phase and the fact that this transformation is more easily accomplished at low temperatures. The amount of transformation that occurs is an interrelated function of chemical composition, temperature, and stress level. The effects of these parameters are discussed in more detail in references 2 and 3. The effect of the transformation on the low-temperature fracture toughness, however, is not fully understood at the present time.

An investigation was begun to determine the tensile properties of cryoformed AISI 301 at temperatures from ambient to the boiling temperature of liquid hydrogen (-423° F). Two finished pressure vessels were obtained that had been fabricated at different forming stress levels (forming stress having been found by the supplier to be indicative of finished vessel performance). These vessels were then cut into tensile coupons, machined to smooth and notched tensile-specimen configurations, and tested at ambient, liquid-nitrogen, and liquid-hydrogen temperatures. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity at the same test temperatures.

Previously unpublished Lewis Research Center data on the properties of 301 stainless steel cold-reduced 60 and 70 percent are presented in this report. The tensile strength and notch strength for the cryoformed material were compared with like properties for this cold-rolled material. Weld strength of the cryoformed material was compared with the strength of roll-planished fusion butt welds in AISI 301 cold-reduced 60 and 78 percent (data from ref. 3).

CRYOFORMING PROCESS

The cryoforming process is described in detail in reference 1, but its essential elements are repeated herein. A sheet of annealed AISI 301 stainless steel is rolled and welded to form a cylinder. Hemispherical heads are usually hydroformed from sheet stock and reannealed. The heads are then welded to the cylinder ends, and a pressurizing boss is welded to one of the heads. All welds are made by the tungsten - inert-gas method. The "preform" tank is then pressurized beyond the elastic limit while at -320° F (liquid-nitrogen temperature). Female dies may be used for more precise control of finished dimensions.

MATERIALS AND TEST SPECIMENS

The cryoformed material was received in the form of two cylindrical tanks with hemispherical ends. (Dimensions and forming parameters are given in table I.) It should be noted that the two tanks were fabricated from the same heat of material but at different forming stress levels. Forming stresses were 267 and 294 ksi, and permanent diametral strains were 14.8 and 15.0 percent.

Tensile coupons 2 by 8 inches, oriented in both the hoop and the axial directions, were cut from the straight cylindrical portions of both tanks. This procedure is illustrated in figure 1. The coupons were then machined to the configurations shown in figure 2. For all notched specimens the notch root radius was not greater than 0.0007 inch (theoretical elastic-stress concentra-

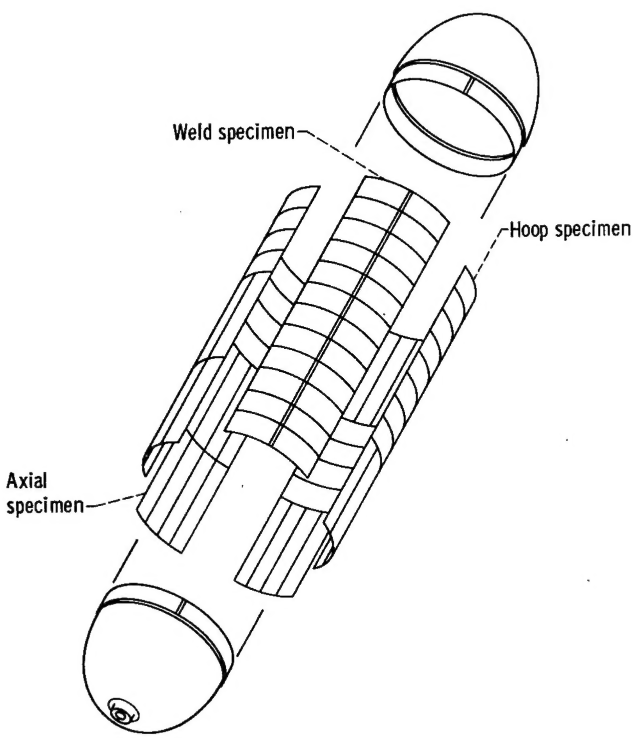


Figure 1. - Cutting of tensile coupons from cylindrical tank.

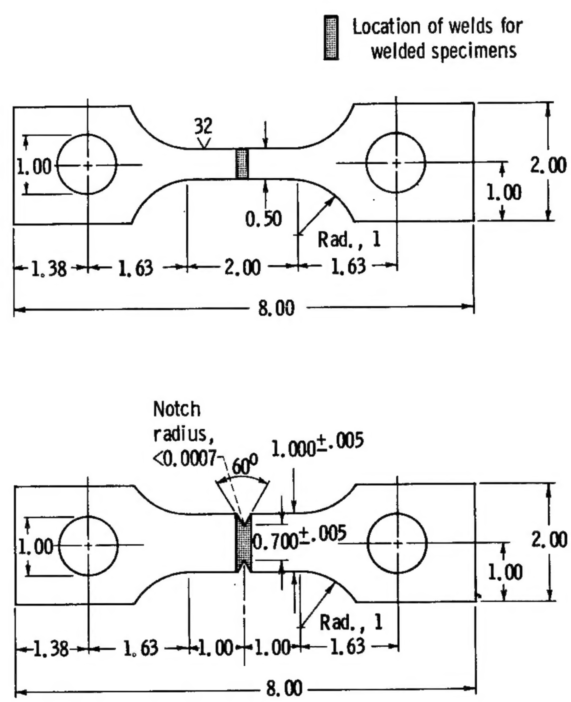


Figure 2. - Smooth- and sharp-notch sheet tensile specimens. (Dimensions in inches.)

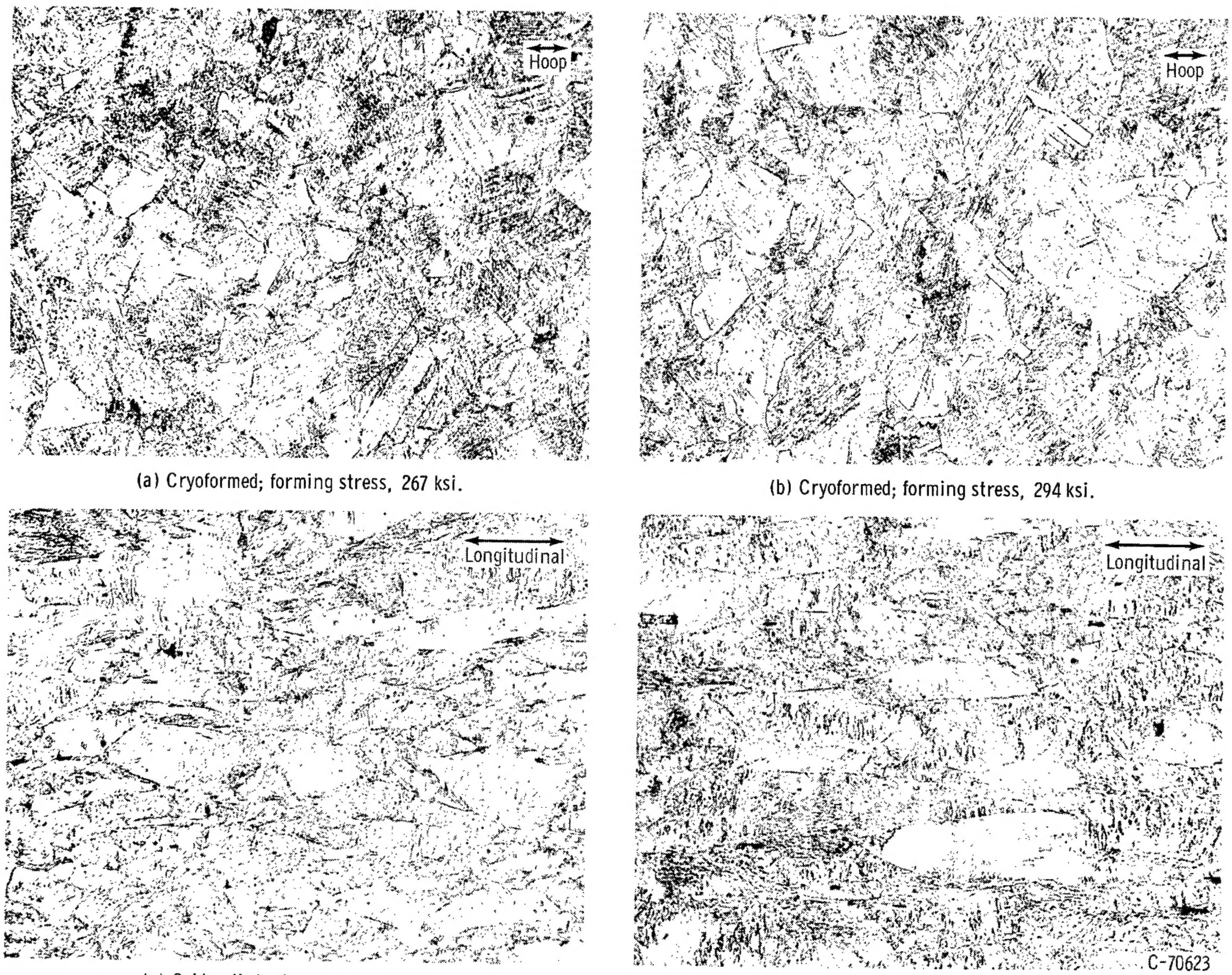
tion factor K_t of 21). No attempt was made to flatten the specimens or to smooth the weld bead. Sufficient coupons were obtained from each tank to test three smooth and three notched specimens in each direction and two smooth-weld and two notched-weld specimens in the hoop direction at each test temperature.

Specimens of the 60- and 70-percent-cold-reduced AISI 301 were cut from sheets and machined to the same configurations as the cryoformed material (fig. 2). At least three specimens were tested at each test condition.

Chemical compositions (where available) of all alloys studied and referenced are presented in table II. Photomicrographs of the cryoformed and cold-reduced AISI 301 materials appear in figure 3.

APPARATUS AND PROCEDURE

Specimens were tested in a universal testing machine. Strain was measured



(a) Cryoformed; forming stress, 267 ksi.

(b) Cryoformed; forming stress, 294 ksi.

(c) Cold-rolled; 60-percent reduction.

(d) Cold-rolled; 70-percent reduction.

Figure 3. - Photomicrographs of materials studied. Etchant, hydrochloric acid and hydrogen peroxide. X250. Reduced 8 percent in printing.

by using a clamp-on linear-variable-differential-transformer extensometer of 2-inch gage length and an autographic stress-strain recorder. The extensometer was previously calibrated at all three test temperatures with a micrometer-driven calibration device.

Cryogenic test temperatures were established by immersing the specimen in liquid nitrogen or liquid hydrogen. A vacuum-jacketed cryostat was used to minimize boiloff. Correct cryogenic temperature was assured by maintaining the liquid level several inches above the upper specimen grip. Liquid level sensing was accomplished by means of a carbon resistor. Details of the cryostat and liquid-level sensing method are described in reference 4.

The smooth tensile strength, the yield strength (0.2-percent offset), and the notch tensile strength were determined at ambient temperature, -320° F, and -423° F for both the hoop and the axial tank directions. Smooth and notched tensile strengths of weld specimens were determined at all three temperatures for the hoop direction only.

CALCULATION OF NOMINAL FRACTURE TOUGHNESS PARAMETER

Evaluation of materials for cryogenic temperature service requires a knowledge of their resistance to brittle fracture, the usual criterion being the fracture toughness parameter K_c. This parameter is derived from tensile tests of smooth and notched specimens. Methods of calculation are given in reference 5 for specimens of various configurations.

The calculation of K_c requires the determination of the total crack length (initial notch length plus slow crack growth) just prior to the onset of rapid fracture. This quantity is difficult to determine, especially when the specimen is immersed in liquid hydrogen. For this reason it becomes expedient to refer to the nominal fracture toughness parameter K_{cn}, which is based only on the original notch length and neglects the slow crack growth. The nominal fracture toughness is never greater than the actual fracture toughness; thus its use leads to a more conservative evaluation of the material.

The equation for K_c is given in reference 5 by equations (21) to (23) for edge-notched tensile specimens, and in its expanded form is

$$K_c^2 = \sigma^2 W\left[\tan\left(\frac{\pi a}{W} + \frac{K_c^2}{2W\sigma_{ys}^2}\right) + 0.1 \sin 2\left(\frac{\pi a}{W} + \frac{K_c^2}{2W\sigma_{ys}^2}\right)\right]$$

where

K_c critical value of plane stress intensity (often referred to as fracture toughness) at point of crack-growth instability in neighborhood of crack

σ gross-section stress at onset of fracture

W specimen width

a half crack length at point of crack instability

σ_{ys} 0.2-percent-offset tensile yield strength

This equation is transcendental; hence either a computer solution or a graphical solution is required. If many specimens are involved and a computer is not available, graphical methods become tedious and a simple approximation would be desirable. If it is assumed that the notched tensile specimen (fig. 2) conforms to the idealized (zero-tolerance) dimensions (i.e., half crack length of 0.150 in. and gross width of 1.000 in.), a curve may be evolved in terms of the nominal fracture toughness parameter, the yield strength, and the notch tensile strength only. This curve is presented in figure 4 and was obtained by using a computer program developed at the Lewis Research Center. As long as the dimensions of the specimen are within the tolerances specified in figure 2, the error resulting from using figure 4 (rather than calculating for the specific dimensions) is less than about 1 percent. This curve applies equally to the ASTM proposed sharp-edge-notch screening specimen (ref. 5, fig. 19), which

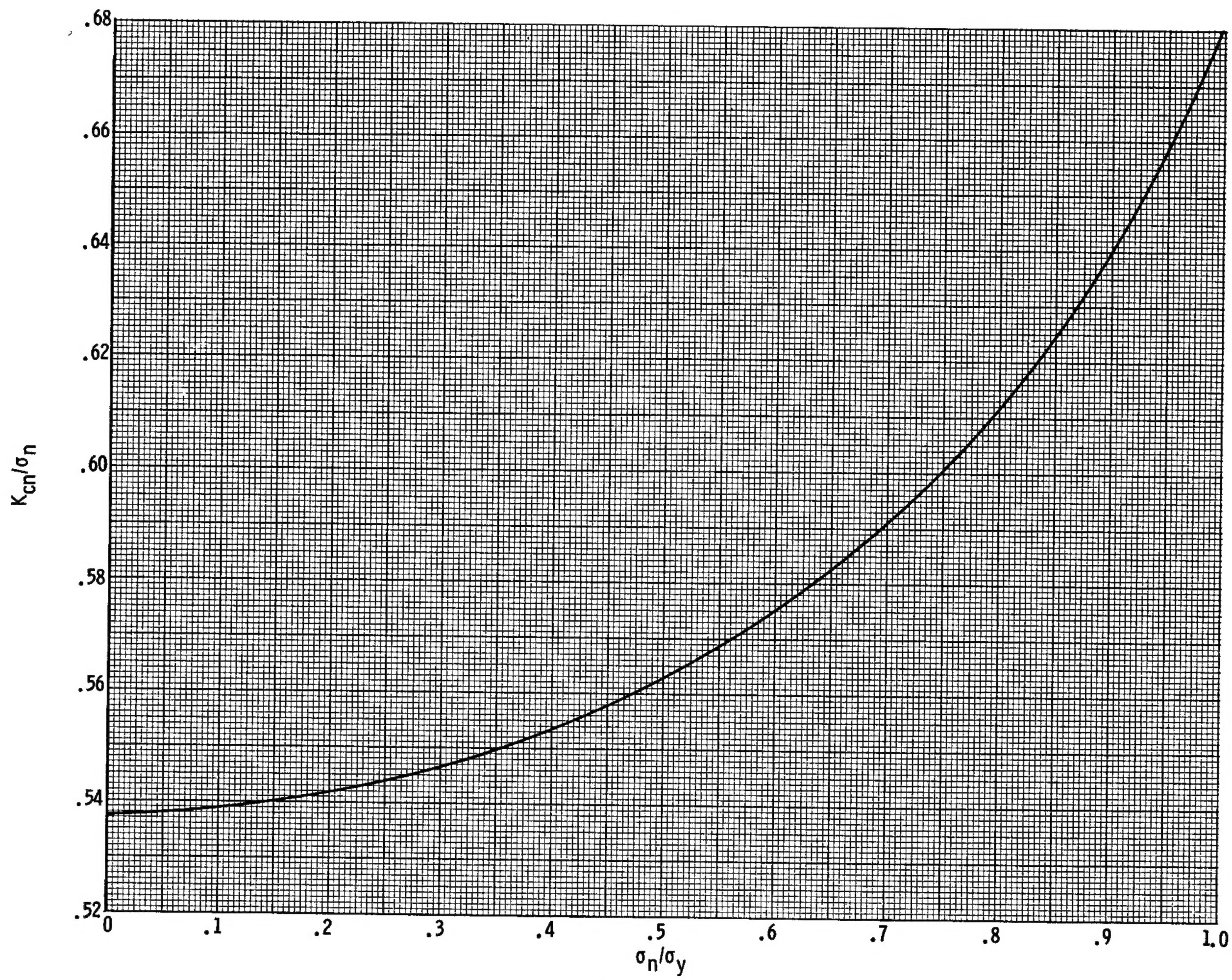


Figure 4. - Nominal fracture toughness parameter for NASA notch tensile specimen. Nominal fracture toughness parameter, K_{cn}; ultimate load divided by area at root of notch, σ_n; conventional yield stress (0.2-percent offset), σ_y.

has an identical test section. The curve has proved to be very useful in studying published data where yield and sharp-notch strengths are given but fracture toughness is not calculated.

RESULTS AND DISCUSSION

Table III lists the average mechanical properties of this heat of AISI 301 stainless steel when cryoformed at two different forming stress levels. Table IV presents corresponding data for a different heat of AISI 301 that was cold-reduced 60 and 70 percent at ambient temperature. Table V lists selected data from reference 3 for comparison of weld strengths.

Parent Metal Properties

The cryoformed parent metal tensile data obtained in this investigation are listed in table III, plotted in figure 5, and compared with like properties (in the direction of maximum working) for the AISI 301 cold-reduced 60 and 70 percent in figure 6. Nominal fracture toughness and notch- to yield-strength ratios are compared in figure 7.

A measure of the experimental scatter is also represented in table III as the average and maximum mean deviations for ultimate, yield, and notch strengths. The average mean deviation is taken as the arithmetic average of the individual deviations (expressed in percent) from their corresponding mean values. The maximum mean deviation represents the largest deviation from a mean value that was observed, signifying for example, that ultimate strength values were (on an average) within ±0.64 percent of their mean values (the values listed in table III) and that the worst point was within 2.69 percent. No such evaluation was made for the weld data because of the smaller number of specimens tested.

Effect of forming stress level. - It is apparent in figures 5 to 7 that the difference between the two samples cryoformed at two different stress levels is slight. A 10-percent increase in forming stress results in a very slight increase in tensile strength and a very slight decrease in notch strength.

These vessels were actually formed by using a two-step process. The vessels were pressurized to about 1100 pounds per square inch (gage pressure) while immersed in liquid nitrogen, removed from the bath, and measured. They were then returned to the liquid-nitrogen bath and pressurized to forming pressure (1175 or 1250 psi).

Subsequent to the fabrication of these vessels, it was found by the supplier of the vessels that, if a tensile specimen was deformed plastically in a liquid-nitrogen bath, removed from the bath for as little as 15 minutes, and then returned to the bath, an increase in the yield strength occurred. The reason for this strengthening is not fully understood at present, but it is believed to be a strain-aging phenomenon.

On this basis it would appear that the final stretching operation given the two vessels resulted in very little additional strengthening due to plastic deformation. Furthermore, since both vessels were initially stretched to very nearly the same forming pressures, it might be expected that their final performances would be similar.

Effect of specimen orientation. - In figure 5 are shown the strength properties of the cryoformed material when tested in the hoop and axial direc-

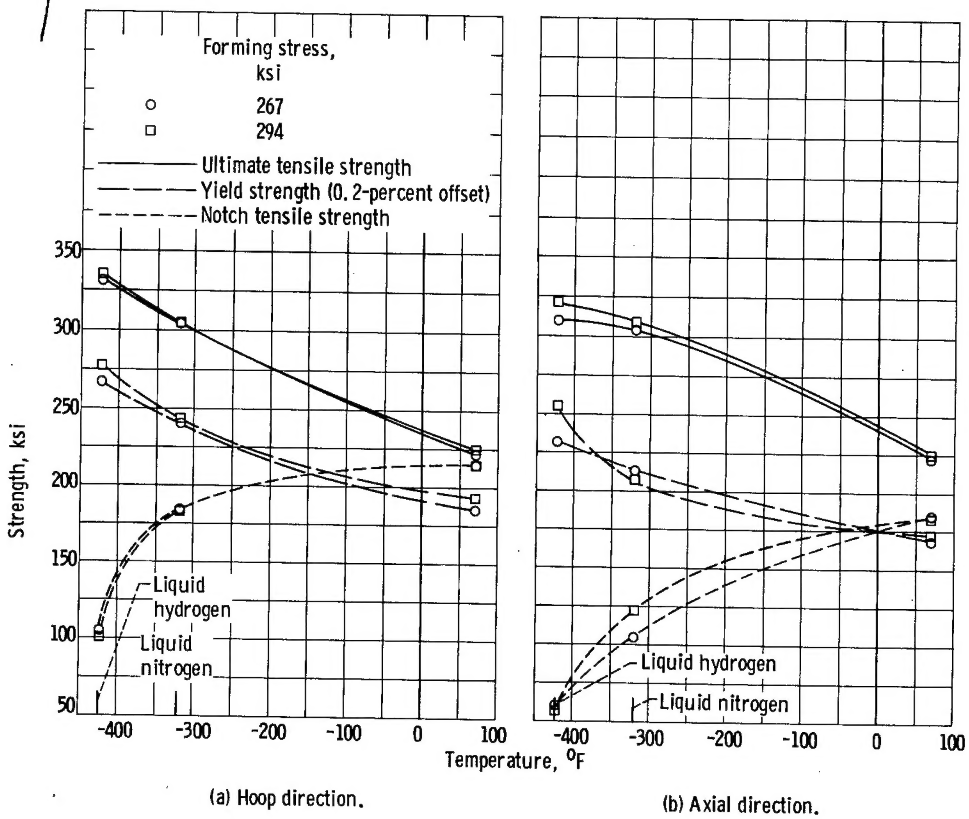
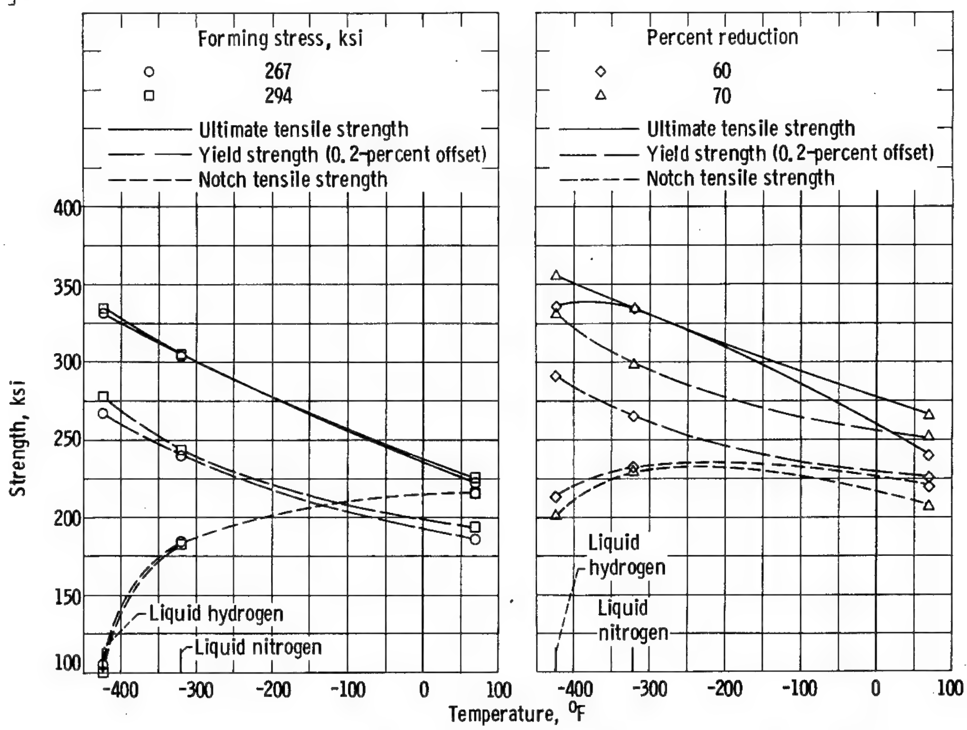


Figure 5. - Strength properties of cryoformed AISI 301 stainless steel as functions of temperature.

tions. These directions are parallel and perpendicular to the direction of maximum mechanical work and correspond to the longitudinal and transverse directions, respectively, in rolled sheet material.

It is of interest to note that the cryoformed AISI 301 exhibits directional characteristics similar to a rolled material, that is, reduced notch strength and slightly reduced yield strength in the direction normal to the direction of maximum work. Since the material was in the annealed condition prior to forming and the amount of mechanical deformation was moderate (when compared with heavy cold-rolling), the material might be expected to be nearly isotropic.

Tensile properties. - In figure 6 the ultimate, yield, and notch tensile strengths for the cryoformed material are compared with like properties for AISI 301 cold-reduced 60 and 70 percent. The ultimate strength of the cryo-



(a) Cryoformed; hoop direction.

(b) Cold-rolled; longitudinal direction.

Figure 6. - Strength properties of cryoformed and cold-rolled AISI 301 stainless steel as functions of temperature.

formed material increases from about 220 ksi at ambient temperature to about 335 ksi at liquid-hydrogen temperature, while the yield strength increases from about 190 to 270 ksi over the same temperature range. At ambient temperature the ultimate and yield strengths for the cryoformed material are about 50 ksi less than for the cold-rolled material, while at -423° F the ultimate strength approaches that of the cold-rolled material.

Notch sensitivity. - It is also shown in figure 6, that the notch tensile strength of the cryoformed material decreases from 215 ksi at ambient temperature to about 100 ksi at -423° F. This decrease is most pronounced below -320° F. The notch strength of the cold-rolled material is above 200 ksi over the same temperature range.

SS

Figure 7 shows the nominal fracture toughness and notch- to yield-strength ratios of the cryoformed and the cold-reduced AISI 301. At ambient temperature the cryoformed material shows a notch- to yield-strength ratio in excess of unity and superior to that of the cold-rolled material. When notch- to yield-strength ratios are in the region of 1.0 and greater, brittle fracture criteria do not apply and calculated fracture toughness values lose significance; hence, they are plotted as dashed lines rather than solid lines. As the test temperature is reduced to -423° F, however, the notch toughness of the cryoformed material falls off considerably. The cold-rolled material retains its notch toughness to -320° F and diminishes somewhat below that temperature.

10

Weld Properties

In figure 8 the weld strengths for the cryoformed AISI 301 are compared with those for AISI 301 cold-reduced 60 and 78 percent and for AISI 304L cold-reduced 50 percent (data from ref. 3). AISI 304L is included in the comparison because of its generally good weldability. Welds in the cryoformed material are work-hardened during the stretch-forming process and were tested exactly as cut from the finished vessels. No attempt was made to flatten the specimens or to smooth the weld bead. Welds in the cold-rolled material were work-hardened after welding by roll-planishing (of the order of 5 to 10 percent reduction) and were probably somewhat stronger than if in the as-welded condition.

The weld strength values for the cryoformed material are based on the parent metal thickness. For the material formed at 294 ksi and tested at -423° F, failures occurred along the edge of the weld bead; whether this was due to a weakness in the heat-affected zone or to a stress concentration at the change in thickness is not immediately apparent. For all other combinations of forming

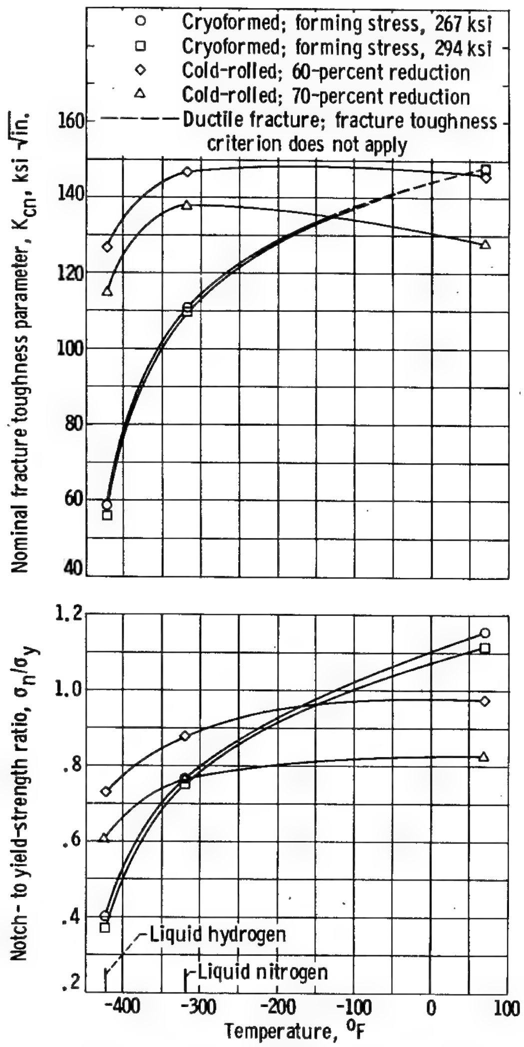


Figure 7. - Nominal fracture toughness parameters and notch- to yield-strength ratios for cryoformed and cold-rolled AISI 301 stainless steels as functions of temperature.

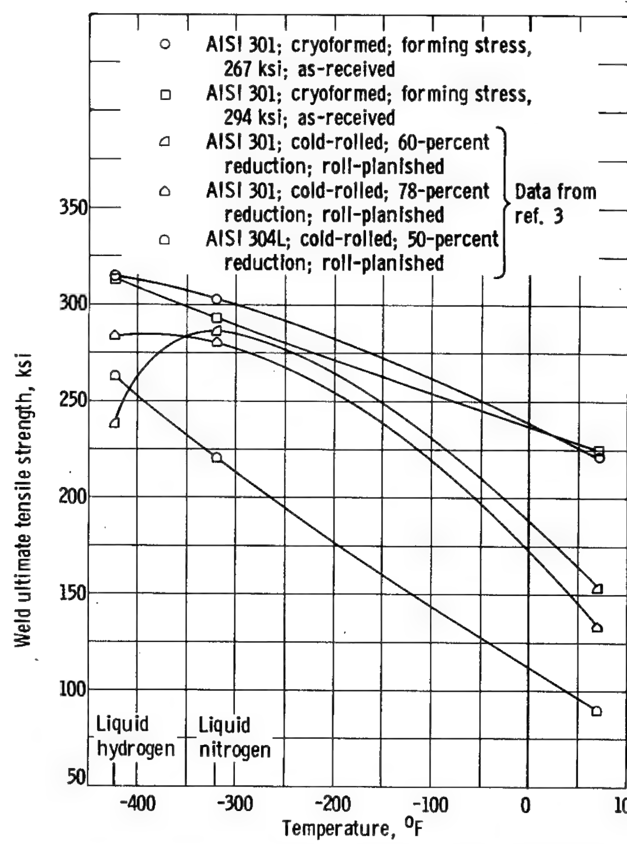


Figure 8. - Weld ultimate tensile strengths for cryoformed AISI 301 and several cold-rolled austenitic stainless steels.

stress and test temperature, failures were well away from the weld area.

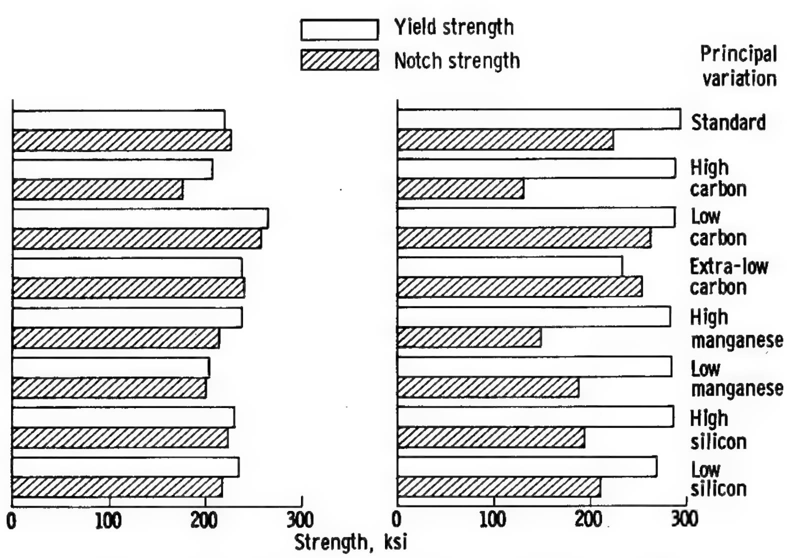
The welds in the cryoformed material are seen to be stronger than those in the cold-rolled material over the temperature range studied. This is most pronounced at ambient temperature, where the cryoformed material has about 50 percent higher weld strength than the cold-rolled AISI 301 and about 150 percent higher weld strength than the cold-rolled AISI 304L. to p. 13

Effect of Variation in Composition

Recent studies indicate that the low-temperature toughness of AISI 301 stainless steel when cold-worked at subzero temperatures may be strongly influenced by its alloying elements. Variations that are within the range of the AISI 301 specification can significantly alter the low-temperature notch strength and fracture toughness.

The screening phase of a program to determine the effects of such variations is reported in reference 6. The nominal 301 composition, as well as 10 individual variations, was studied. Materials were cold-reduced 20 and 40 percent at roll entry temperatures of 80° and -105° F and stress-relieved at 800° F for 24 hours. Notch strength was determined from centrally fatigue-cracked specimens, and a compliance gage was used to determine slow crack growth.

In figure 9 are shown selected data from reference 6. It is immediately apparent that the effects of composition variations are less pronounced when the material is rolled at ambient temperature (fig. 9(a)) than when it is rolled at subzero temperature (fig. 9(b)). It is also apparent that the notch strength is affected more strongly than the yield strength.



Principal variation	Carbon	Silicon	Manganese
Standard	0.134	0.41	1.04
High carbon	.23	.56	.45
Low carbon	.075	.42	.64
Extra-low carbon	.014	.27	.58
High manganese	.158	.40	1.25
Low manganese	.165	.51	.33
High silicon	.155	.98	.92
Low silicon	.140	.27	.88

(Percent composition)

(a) Roll entry temperature, 80° F. (b) Roll entry temperature, -105° F.

Figure 9. - Yield and notch strengths of various AISI 301-type compositions cold-reduced 40 percent, stress-relieved at 800° F for 24 hours, and tested at -200° F (data from ref. 6).

In light of the results of reference 6, it might be expected that the effects of alloy variations would be even more pronounced when the material is work-hardened at -320° F rather than at -105° F. Since the manner of introducing mechanical work differs, cryogenic stretch-forming cannot be directly compared with subzero rolling; however, the same general trends might be expected.

Reported in reference 7 are the results of a somewhat similar research program. Selected data from this reference are presented in table VI, along with values of nominal fracture toughness (K_{cn}) that were calculated by the present author using the referenced values for yield and notch strengths together with the curve of figure 4. Even when tested at ambient temperature, a wide variation in notch strengths can be seen. Unfortunately, only two compositions were tested at -320° F, but even so their notch strengths differ markedly.

Preliminary Evaluation of Special Composition

To support the supposition that notch toughness of cryoformed AISI 301 could be improved by a change in alloy content, a limited amount of data has been generated from a special heat of material (number 40226) having low carbon, low silicon, and low manganese content. These data are presented in table VII. Specimens were rough-shaped and then stretched in uniaxial tension at -320° F to about 270 ksi (forming stress). One group of specimens was also stress-relieved at 790° F for 20 hours. Specimens were then finish-machined to the configurations in figure 2 and tested at ambient temperature, -320° F, and -423° F. The ambient and -320° F testing was done by the supplier; the -423° F testing was done at the Lewis Research Center. Results are listed in table VII. These data represent only one specimen per condition and therefore should be interpreted accordingly. Furthermore, this material was stretched in uniaxial rather than biaxial tension.

Examination of these data shows that, while the ultimate strength of the as-stretched specimen is about 10 ksi lower than that of the biaxially stretched material from heat number M58044, the notch tensile strength at -423° F is more than twice as great. Furthermore, both smooth and notched strengths increase upon stress relief. Although a direct comparison may not be entirely valid, these data indicate that poor low-temperature notch toughness may not be an inherent characteristic of cryogenic stretch-forming.

Advantages and Limitations of Cryoforming

Perhaps the most outstanding advantages of the cryoforming method are the relative ease of fabrication, the excellent weld strength, and the nearly ideal structure (from the viewpoint of the stress analyst) that result. All material is cut, shaped, and welded while in the annealed condition. Cylindrical vessels with hemispherical or elliptical ends as well as spherical or ellipsoidal vessels without flanges can be made. Furthermore, a method has been developed whereby a cylindrical vessel with hemispherical ends may be cryoformed from a configuration made up entirely from flat sheet stock. Weld performance is excellent, with strengths practically indistinguishable from those of the parent

metal. There are no spot welds, thickened sections, abrupt changes in contour or thickness, heat treatments, or post-heat-treatment straightening operations to contend with.

The amount of mechanical work that may be introduced by cryogenic stretch-forming is limited by tensile instability considerations, which are not present in cold-rolling. Hence, a material is required whose strengthening comes from metallurgical transformation as well as from mechanical working. AISI 301 stainless steel has been found to experience the highest strength increase for a given amount of strain.

For service at ambient temperatures, the cryoforming process appears very attractive; for cryogenic applications the picture is not yet clear. Considering only the tensile coupon tests, it would appear that a more desirable method of fabrication has been attained, but an inferior material has resulted. There are not enough data at present, however, to determine whether the poor low-temperature toughness is an inevitable consequence of cryogenic stretch-forming or whether it is due to the choice of an alloy composition basically unsuitable for this process.

Limited data generated in this report on the special heat (number 40226) would suggest that the problem is not inherent and that a significant improvement can be made; however, a definite conclusion cannot be reached without further investigation.

SUMMARY OF RESULTS

The results of tensile coupon tests of cryoformed AISI stainless-steel pressure vessels at cryogenic temperatures indicate that cryogenic stretch-forming appears to be a promising method for fabricating lightweight high-strength pressure vessels but that AISI 301 of the specific composition studied, when stretch-formed at -320° F, is unsuitable for service at -423° F because of its poor notch toughness. The results may be summarized as follows:

1. The ultimate and yield strengths of the cryoformed AISI 301 increased by about 50 percent as the test temperature was reduced from ambient to -423° F but were lower than those of the AISI 301 cold-reduced 60 and 70 percent.

2. Weld efficiencies were excellent, being above 93 percent (in the as-received condition) for all cases.

3. The material tested was notch ductile at ambient temperature but became notch sensitive at cryogenic temperatures with notch- to yield-strength ratios as low as 0.223 (in the transverse direction) at -423° F.

Comparison of the data of other investigators with the data obtained in this investigation leads to the following conclusions:

1. Weld strengths attainable in cryoformed pressure vessels are higher than those for roll-planished fusion welds in cold-rolled materials over the

temperature range studied.

2. It appears possible that the low notch toughness of this material at cryogenic temperatures could be improved by a change in the alloy content, but further research is needed to determine the effect of composition on the properties of AISI 301 when worked at subzero temperatures and to determine the optimum composition for cryogenic service.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 17, 1964

REFERENCES

1. Alper, R. H.: Development of Ultra High Strength Rocket Motor Cases by Cryogenic Stretch Forming. Arde-Portland, Inc., Feb. 15, 1962.

2. Krivobok, V. N., and Talbot, A. M.: Effect of Temperatures on the Mechanical Properties, Characteristics, and Processing of Austenitic Stainless Steels. Proc. ASTM, vol. 50, 1950, pp. 895-928; discussion, pp. 929-930.

3. Watson, J. F., and Christian, J. L.: A Study of Austenite Decomposition at Cryogenic Temperatures. Rep. ERR-AN-057, General Dynamics/Astronautics, June 9, 1961.

4. Hanson, Morgan P.: Smooth and Sharp-Notch Tensile Properties of Cold-Reduced AISI 301 and 304L Stainless-Steel Sheet at 75°, -320°, and -423° F. NASA TN D-592, 1961.

5. Special ASTM Committee: Fracture Testing of High-Strength Sheet Materials. Ch. I. ASTM Bull., Jan. 1960, pp. 29-40.

6. Morrison, J. D., Campbell, M. A., and Kattus, J. R.: Development of High Strength and Fracture Toughness in Steels Through Strain-Induced Transformations. Third Quarterly Prog. Rep., Jan. 1-Mar. 31, 1963, Southern Res. Inst., May 10, 1963.

7. Floreen, S., and Mihalisin, J. R.: High Strength Stainless Steel by Deformation at Low Temperatures. Tech. Paper 361, International Nickel Co., Nov. 7, 1962.

TABLE I. - VESSEL PARAMETERS

[Material heat number M58044.]

	Vessel serial number	
	1504	1505
Before forming		
Outside diameter, in.	11.035	11.035
Wall thickness, in.	0.032	0.032
Cylinder length, in.	33	33
After forming		
Outside diameter, in.	12.671	12.690
Forming strain, percent	14.8	15.0
Wall thickness, in.	0.0287	0.0287
Forming pressure, psi	1175	1250
Forming stress (hoop), ksi	267	294

TABLE II. - CHEMICAL COMPOSITIONS OF ALLOYS STUDIED AND REFERENCED

[Compositions in percent by weight.]

Alloy	Condition	Sulfur	Phos-pho-rous	Carbon	Man-ga nese	Sili-con	Chro-mium	Nickel	Nitro-gen	Oxygen	Hydro-gen	Heat number	Source
AISI 301	Cryoformed	0.015	0.027	0.075	1.55	0.41	17.19	7.53	0.045	0.018	0.0003	M58044	This report
	Cold-rolled; 60- and 70-percent reduction	.013	.024	.11	1.02	.38	17.43	7.21	.044	.022	.0006	97838	
	Special heat	.006	.006	.032	.04	.01	18.90	7.65	.015	.010	------	40226	
AISI 301	Cold-rolled; 60-percent reduction	0.022	0.026	0.07	0.97	0.41	17.74	6.87	-----	-----	------	48112	Reference 3
AISI 301	Cold-rolled; 78-percent reduction	.015	.032	.09	1.83	.42	17.78	7.35	-----	-----	------	152753	
AISI 304L	Cold-rolled; 50-percent reduction	.11	.026	.023	1.54	.66	18.04	10.39	-----	-----	------	33251	
AISI 301 Standard	Cold-rolled	0.018	0.010	0.134	1.04	0.41	17.61	7.56	-----	-----	------	None	Reference 6
High carbon		.011	.007	.23	.45	.56	17.70	6.97	-----	-----	------		
Low carbon		.015	.007	.075	.64	.42	17.0	8.12	-----	-----	------		
Extra low carbon		.019	.010	.014	.58	.27	17.5	7.13	-----	-----	------		
High manganese		.010	.007	.158	1.25	.40	17.6	6.92	-----	-----	------		
Low manganese		.014	.011	.165	.33	.51	16.7	7.70	-----	-----	------		
High silicon		.020	.009	.155	.92	.98	16.73	7.93	-----	-----	------		
Low silicon		.016	.008	.140	.88	.27	15.95	7.29	-----	-----	------		
Alloy 1	Vacuum-melted	-----	-----	0.05	0.95	0.09	18.0	7.6	0.01	-----	------	None	Reference 7
2		-----	-----	.04	.45	.10	19.8	10.1	.01	-----	------		
3		-----	-----	.04	.72	.11	18.3	10.3	.01	-----	------		
4		-----	-----	.04	.67	.12	18.8	6.7	.01	-----	------		
5		-----	-----	.05	.48	.07	17.0	5.3	.01	-----	------		
6		-----	-----	.05	.78	.11	18.9	7.7	.01	-----	------		
7		-----	-----	.06	.75	.10	18.8	8.6	.01	-----	------		
8		-----	-----	.05	.01	.10	18.4	8.2	.01	-----	------		
9		-----	-----	.05	.47	.57	18.6	8.8	.01	-----	------		
Alloy 10	Air-melted	-----	-----	0.07	0.05	0.13	18.7	7.4	0.02	-----	------	None	Reference 7
11		-----	-----	.05	.92	.50	18.4	9.0	.02	-----	------		
12		-----	-----	.04	1.01	.01	18.4	9.0	.03	-----	------		
13		-----	-----	.04	.81	.44	18.5	7.7	.05	-----	------		
14		-----	-----	.05	.82	.46	18.5	8.1	.03	-----	------		
15		-----	-----	.06	.13	.13	18.7	8.1	.05	-----	------		
16		-----	-----	.08	.25	.05	17.7	6.0	.04	-----	------		
17		-----	-----	.08	.21	.08	17.7	5.5	.03	-----	------		

TABLE III. - AVERAGE TENSILE PROPERTIES OF CRYOFORMED AISI 301 STAINLESS STEEL

[Heat number M58044.]

Vessel serial number	Forming stress, ksi	Direction	Test temperature, °F	Ultimate tensile strength, ksi	Yield strength (0.2-percent offset), ksi	Sharp-notch tensile strength, ksi	Notch- to yield-strength ratio	Nominal fracture toughness, ksi $\sqrt{in.}$	Weld ultimate tensile strength, ksi	Weld- to parent-ultimate-tensile-strength ratio	Weld notch tensile strength, ksi	Weld- to parent-notch-tensile-strength ratio
1504	267	Hoop	Ambient	222	186	215	1.156	(a)	221	0.995	216	1.005
			-320	304	241	184	.764	111	303	.997	169	.918
			-423	332	267	106	.397	59	316	.952	97	.915
		Axial	Ambient	224	168	184	1.094	(a)	---	-----	---	-----
			-320	304	213	105	.491	59	---	-----	---	-----
			-423	310	232	59	.255	32	---	-----	---	-----
1505	294	Hoop	Ambient	224	193	215	1.114	(a)	224	1.000	217	1.010
			-320	305	243	183	.753	110	293	.961	161	.880
			-423	335	278	101	.363	56	313	.933	90	.894
		Axial	Ambient	228	172	183	1.072	(a)	---	-----	---	-----
			-320	309	207	122	.589	70	---	-----	---	-----
			-423	321	255	57	.223	31	---	-----	---	-----
Average mean deviation, percent				0.64	1.68	4.01	-----	---	---	-----	---	-----
Maximum mean deviation, percent				2.69	5.16	15.8	-----	---	---	-----	---	-----

[a]Ductile fracture; fracture toughness criterion does not apply.

TABLE IV. - AVERAGE TENSILE PROPERTIES OF COLD-REDUCED AISI 301 STAINLESS STEEL

[Heat number 97838.]

Percent cold reduction	Thickness, in.	Direction	Test temperature, $^{\circ}F$	Ultimate tensile strength, ksi	Yield strength (0.2-percent offset), ksi	Sharp-notch tensile strength, ksi	Notch- to yield-strength ratio	Nominal fracture toughness, ksi $\sqrt{in.}$
60	0.022	Longitudinal	Ambient	239	225	219	0.974	146
			-320	335	264	232	.879	147
			-423	336	291	213	.732	127
		Transverse	Ambient	249	210	180	0.867	113
			-320	342	257	139	.541	79
			-423	336	306	135	.441	75
70	0.022	Longitudinal	Ambient	264	251	207	0.824	128
			-320	334	298	229	.768	138
			-423	355	330	200	.606	115
		Transverse	Ambient	274	224	143	0.586	82
			-320	348	285	125	.439	70
			-423	363	327	116	.355	64

TABLE V. - TENSILE PROPERTIES OF AUSTENITIC STAINLESS STEELS FOR WELD STRENGTH COMPARISON

[Data from ref. 3.]

AISI alloy	Percent cold reduction	Thickness, in.	Direction	Test temperature, °F	Ultimate tensile strength, ksi	Yield strength (0.2-percent offset), ksi	Weld ultimate tensile strength, ksi	Weld- to parent-ultimate-tensile-strength ratio
301	60	0.023	Longitudinal	70 -320 -423	212 313 317	200 248 291	153 287 238	0.722 .917 .751
301	78	0.016	Longitudinal	70 -320 -423	298 367 423	291 350 423	133 281 284	0.446 .765 .671
304L	50	0.012	Longitudinal	70 -320 -423	176 251 279	158 187 231	90 221 263	0.511 .880 .943

TABLE VI. - TENSILE PROPERTIES OF SEVERAL 301-TYPE COMPOSITIONS

[Data from ref. 7; nominal sheet thickness, 0.060 in.; cold-reduced 40 percent at -106° F; stress-relieved at 800° F for 24 hours.]

Composition, percent by weight							Test temperature, °F	Ultimate tensile strength, ksi	Yield strength (0.2-percent offset), ksi	Notch tensile strength, ksi	Nominal fracture toughness, ksi $\sqrt{\text{in.}}$
Alloy	Nickel	Chromium	Manganese	Silicon	Carbon	Nitrogen					
[c]11	9.0	18.4	0.92	0.50	0.05	0.02	Room	254	246	222	142
[b]5	5.3	17.0	.48	.07	.05	.01		209	203	229	(a)
[c]17	5.5	17.7	.21	.08	.08	.03		235	232	234	(a)
[c]13	7.7	18.5	.81	.44	.04	.05		261	261	236	152
[c]12	9.0	18.4	1.01	.01	.04	.03		240	236	238	(a)
[c]14	8.1	18.5	.82	.46	.05	.03		255	254	238	155
[b]2	10.1	19.8	.45	.10	.04	.01		232	222	241	(a)
[b]9	8.8	18.6	.47	.57	.05	.01		264	254	246	164
[b]4	6.7	18.8	.67	.12	.04	.01		251	251	247	166
[c]15	8.1	18.7	.13	.13	.06	.05		239	237	249	(a)
[c]16	6.0	17.7	.25	.05	.08	.04		251	249	252	(a)
[b]1	7.6	18.0	.95	.09	.05	.01		264	263	252	167
[b]6	7.7	18.9	.78	.11	.05	.01		263	262	261	177
[b]7	8.6	18.8	.75	.10	.06	.01		250	249	262	(a)
[b]8	8.2	18.4	.01	.10	.05	.01		259	257	271	(a)
[c]10	7.4	18.7	.05	.13	.07	.02		274	274	277	(a)
[c]14	8.1	18.5	.82	.46	.05	.03	-320	313	312	223	132
[c]15	8.1	18.7	.13	.13	.06	.05	-320	297	296	300	(a)

[a]Ductile fracture; fracture toughness criterion does not apply.

[b]Vacuum-melted.

[c]Air-melted.

TABLE VII. - PRELIMINARY DATA ON TENSILE PROPERTIES

OF SPECIAL HEAT NUMBER 40226

[Forming stress, 270 ksi in uniaxial tension at -320° F; specimens tested in same direction as forming stress.]

Condition	Test temperature, °F	Ultimate tensile strength, ksi	Yield strength (0.2-percent offset), ksi	Notch tensile strength, ksi	Notch- to yield-strength ratio
As-stretched	Ambient	206	204	236	1.16
	-320	288	286	268	.94
	-423	319	316	232	.73
Stress-relieved at 790° F for 20 hours	Ambient	242	241	249	0.86
	-320	308	305	269	.88
	-423	334	330	264	.80

NASA TN D-2202
National Aeronautics and Space Administration.
TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES. Thomas W. Orange. October 1964. 21p. OTS price, $0.75. (NASA TECHNICAL NOTE D-2202)

Cylindrical pressure vessels that had been fabricated by cryoforming (cryogenic stretch forming) were cut into coupons from which smooth and sharp-notch tensile specimens were made. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity. Specimens were tested at ambient temperature, -320° F, and -423° F. Results were compared with like properties for AISI 301 stainless steel cold-reduced 60 and 70 percent.

I. Orange, Thomas W.
II. NASA TN D-2202

NASA

NASA TN D-2202
National Aeronautics and Space Administration.
TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES. Thomas W. Orange. October 1964. 21p. OTS price, $0.75. (NASA TECHNICAL NOTE D-2202)

Cylindrical pressure vessels that had been fabricated by cryoforming (cryogenic stretch forming) were cut into coupons from which smooth and sharp-notch tensile specimens were made. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity. Specimens were tested at ambient temperature, -320° F, and -423° F. Results were compared with like properties for AISI 301 stainless steel cold-reduced 60 and 70 percent.

I. Orange, Thomas W.
II. NASA TN D-2202

NASA

NASA TN D-2202
National Aeronautics and Space Administration.
TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES. Thomas W. Orange. October 1964. 21p. OTS price, $0.75. (NASA TECHNICAL NOTE D-2202)

Cylindrical pressure vessels that had been fabricated by cryoforming (cryogenic stretch forming) were cut into coupons from which smooth and sharp-notch tensile specimens were made. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity. Specimens were tested at ambient temperature, -320° F, and -423° F. Results were compared with like properties for AISI 301 stainless steel cold-reduced 60 and 70 percent.

I. Orange, Thomas W.
II. NASA TN D-2202

NASA

NASA TN D-2202
National Aeronautics and Space Administration.
TENSILE COUPON TESTS OF CRYOFORMED AISI 301 STAINLESS-STEEL PRESSURE VESSELS AT CRYOGENIC TEMPERATURES. Thomas W. Orange. October 1964. 21p. OTS price, $0.75. (NASA TECHNICAL NOTE D-2202)

Cylindrical pressure vessels that had been fabricated by cryoforming (cryogenic stretch forming) were cut into coupons from which smooth and sharp-notch tensile specimens were made. Coupons from the longitudinal-seam-weld area were used to evaluate weld efficiency and notch sensitivity. Specimens were tested at ambient temperature, -320° F, and -423° F. Results were compared with like properties for AISI 301 stainless steel cold-reduced 60 and 70 percent.

I. Orange, Thomas W.
II. NASA TN D-2202

NASA

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—National Aeronautics and Space Act of 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546